The Origin of Grooved Terrain on Ganymede: Insights from Galileo High-Resolution Imaging. R. T. Pappalardo[1], J. W. Head[1], G. C. Collins[1], R. Greeley[2], and The Galileo SSI Team, [1]Brown Univ. (Dept. Geol. Sci., Box 1846, Providence, RI 02912; pappalardo@brown.edu), [2]Arizona State Univ. (Geology Dept., Box 871404, Tempe, AZ 85287).

The first two orbits of the Galileo spacecraft through the jovian system saw two close encounters with Ganymede. Imaging of Ganymede's bright grooved terrain is a primary objective of the SSI instrument, in order to elucidate the nature, origin, and evolution of grooved terrain and its constituent structures. Galileo images are in agreement with the basic elements of the Voyager-based view in which grooved terrain formation is dominated by extensional tectonism, likely in combination with icy volcanism, but Galileo images reveal remarkable new insights into the process of grooved terrain formation, including: 1) the prevalence of small-scale structures interpreted as domino-style tilt blocks, and an inferred change in tectonic style from horst-and-graben to domino-style through time; 2) the ability for tectonism alone (in the absence of icy volcanism) to "resurface" lanes of bright terrain; 3) the importance of a shear component in grooved terrain formation; 4) the presence of integrated patterns of contemporaneous deformation; 5) revised stratigraphic interpretations for bright terrain units based on cross-cutting relationships; and 6) the presence of multiple wavelengths of deformation within grooved terrain. Thus, the Galileo observations provide a basis for important modifications to previously proposed models for the formation of Ganymede's grooved terrain.

Observation objectives. Grooved terrain on Ganymede consists of sets of subparallel ridges and troughs, typically organized in structural cells within broader swaths of bright terrain; based on Voyager images, morphological evidence generally indicates an extensional-tectonic origin for the ridges and troughs, likely as normal fault blocks [1]. Galileo observations of grooved terrain have been designed to address specific questions regarding: the nature and origin of its constituent ridges and troughs, the deformation style and strain represented, the stratigraphy and emplacement history of the terrain, the relationship of tectonism to the resurfacing process, whether a single or multiple processes has operated to form grooved terrain, the implications of the spacing of its ridges and troughs, and the implications for the history of Ganymede and other icy satellites [2]. Discussion here concentrates on the high resolution images of Uruk Sulcus obtained on Galileo's first orbit, G1. The G2 grooved terrain targets are described in companion abstracts by Head et al. and Pappalardo et al. (this volume). Relevant images may be seen at http://www.jpl.nasa.gov/galileo/sepo/atjup/ganymede/ganymede.html.

Morphology and deformation styles of grooved terrain at high resolution. On its first orbit, Galileo obtained 4 images at ~75 m/pxl of a region of bright grooved terrain within Uruk Sulcus, centered at 11.1°N, 168.9°W and covering an area approximately 100 x 120 km [3]. Sections of two additional images were obtained on Galileo's second orbit at ~45 m/pixel, providing stereo data across a part of this area. Contrast variations in the Uruk Sulcus images are extreme, and the stereo imaging confirms that albedo variations are controlled by topography (for example, small-scale albedo striping defines ridges and troughs, and dark material appears to collect in topographic lows); thus, landform morphology and structure can be recognized in Ganymede's grooved terrain even under these conditions of high solar illumination ($i \approx 13°$).

The high resolution images show that ridges and grooves are pervasive at the small scale. For example, groove lanes interpreted to contain roughly 5 ridges at Voyager scale display an order of magnitude more ridges at the Galileo scale [3]. We broadly categorize the morphology of ridges and troughs across the Uruk Sulcus mosaic as of two types: 1) plank-like, flat-topped fractured ridges separated by prominent (low albedo) fractures inferred to be relatively deep troughs, as seen in the northeastern corner of the Uruk Sulcus mosaic (the type example is the PLT2 unit of Senske et al. [this volume]), and 2) ridges of triangular to somewhat rounded cross-section, typically comprised of a bright western face and separated by dark-bottomed, relatively triangular troughs, as occur in NW-SE trending groove lanes (the type example is the PRT1 unit of Senske et al. [this volume]). The plank-like ridges have morphologies that closely match the morphological predictions of horst and graben style normal faulting, while the triangular ridges that dominate the younger groove lanes have morphologies and associations matching the predictions of tilt block ("domino") style normal faulting, in which extension causes rotation of faults and the original surface by an amount proportional to the amount of extension [4]. Relationships along the margins of groove lanes strongly support these extensional tectonic models, as the density of fractures marking distinct groove lanes rapidly dissipates at groove lane margins, while a few incipient fractures are observed to splinter this adjacent terrain. Domino-style normal faulting implies a high degree of extensional strain relative to horst-and-graben style faulting [5]. Preliminary estimates indicate ~50% extension across lanes of tilt-block style normal faults in Uruk Sulcus, much greater than the ~1% strain estimates obtained by assuming that groove lanes are comprised of a few simple graben bounded by individual steeply dipping faults [6].

In general, the groove polygons that show horst-and-graben morphology have a relatively high crater density, indicating that they are relatively old. Moreover, their constituent structures are oriented NE-SW to N-S, suggesting extension perpendicular to these trends during their formation. These polygons are cross-cut by groove lanes that consist of domino-style normal faults and which show lesser crater densities, indicating that they are younger. These groove lanes and their constituent structures are oriented NW-SE, indicative of NE-SW extension. The general correlation of faulting style with relative terrain age implies that there has been a general change from horst-and-graben to domino style faulting over time. This may reflect change in the strain, strain rate, and/or thermal gradient with time during grooved terrain formation. Moreover, there appears to have been a counterclockwise rotation of principal stress orientation during formation of grooved terrain in Uruk Sulcus [Collins et al., this volume].

Truncation of NE-SW trending structures by younger NW-SE trending structures contradicts a proposed sequence in which structures terminate abruptly in "T-terminations" when encountering older structures [7]. Instead, Galileo images of Uruk Sulcus show that structures forming the cross-bar of the T are the younger, having cross-cut older structures of the T stem. A deep trough marking the edge of a groove lane might be a reactivated primary structure [8]. Moreover, this prominent bounding depression may reflect rollover of the hanging wall block of the normal fault zone above a prominent marginal fault [cf. 9].

The units that are most heavily cratered at Galileo resolution appear at Voyager resolution to be relatively smooth. This is apparently the result of impact gardening having produced topography that is smooth relative to younger, sparsely cratered regions of grooved terrain which have substantial tectonically-generated relief. Based on Voyager images, smooth terrains were typically interpreted as of cryovolcanic origin and placed high in the stratigraphic column [10]. Galileo images show that some smooth terrain can be heavily cratered and can be some of the region's oldest terrain.

As addressed by Head et al. (this volume), there is little direct evidence for cryovolcanism in the Uruk Sulcus region imaged by Galileo. Furthermore, there is evidence that tilt-block style normal faulting has modified pre-existing terrain through destruction of the pre-existing surface, including its craters. It appears that rotational normal faulting alone is capable of "tectonically resurfacing" groove lanes on Ganymede. Cryovolcanism is not excluded as an integral part of the grooved terrain emplacement process [Head et al., this volume; Pappalardo et al., this volume]; however, the dearth of recent, identifiable cryovolcanic features in the Uruk Sulcus region implies that cryovolcanism may have been played a relatively minor and/or early role in the grooved terrain emplacement sequence, with any widespread cryovolcanic units having been tectonically modified during or since their formation.

Fourier analysis of photometric profiles across groove sets imaged by Galileo suggests the addition of multiple wavelengths of deformation during grooved terrain formation. For example, the prominent groove lane in the southwestern portion of the Uruk Sulcus mosaic shows constituent wavelengths of ~0.7, 1.3, and 1.9 km [Sun et al, this volume]. Moreover, digital elevation models constructed from the G2 stereo imaging data indicate a broad wavelength of deformation [Giese et al., this volume] which likely correlates to the Voyager-inferred topographic wavelength [11]. We associate this broad scale of deformation with an origin by necking of Ganymede's lithosphere [Collins et al., this volume], while the finer scale of deformation may reflect brittle faulting of the surface layer to the base of a cryovolcanic layer and additional imbrication of these faults into a finer wavelength scale in regions of greatest local strain.

Evidence for shear and transtension. Within a prominent, ~7 km wide, stratigraphically high zone that cuts NW-SE across the Galileo Uruk Sulcus mosaic (unit EERT of Senske et al. [this volume]), we recognize many left-stepping en echelon, sigmoidal shaped blocks. At its eastern imaged extent, this zone bends toward the southeast; just west of this bend is a unit consisting of elongate, sigmoidal blocks that mimic the shape and dimensions of the bend (unit PRTS of Senske et al. [this volume]). The sigmoidal structures within this unit and the spindle-shapedridges beside it indicate that right-lateral horizontal shear likely acted along this unit, with the spindle-shaped ridges and troughs being a fault duplex formed in the releasing bend of a dextral strike-slip zone. Consistent with this shear zone interpretation is a trough ~7 km wide which tapers away from the zone of en echelon structures (i.e. extending from northward from unit EERT into unit ST1 of Senske et al. [this volume]), which is interpreted here as a "horsetail" structure induced by the neighboring dextral strike-slip motion. Based on inferred structural displacements, right-lateral motion along the imaged segment of the shear zone was likely a few km or less.

The stratigraphically high structures interpreted as associated with shearing do not appear to cross-cut the stratigraphically high groove lanes that we interpret as due to domino-style faulting in response to NE-SW-directed extension (units PRT1 and PRT2 of Senske et al. [this volume]). Indeed, these groove lanes and the shear-related structures could have formed contemporaneously. The predicted structural pattern of dextral simple shear [12] closely matches the sense and orientation of the stratigraphically high structures in Uruk Sulcus, with the lanes of domino fault blocks being perpendicular to the long axis of the regional strain ellipse and the prominent shear zone serving as a Reidel shear. The lack of recognizable compressional features in the region suggests that transtension affected the area, emphasizing the extensional deformation, and this implies regional tension nearly perpendicular to the shear direction [13] during this late-stage deformational episode. The recognition of contemporaneous formation of an integrated pattern of structures of different orientations has important implications for interpretation of the stratigraphy and evolution Ganymede's grooved terrain.

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